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EVIDENCE FOR THE EFFECT OF CORPUSCULAR RADIATION ON THE IONOSPHERE

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ABSTRACT

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The correlation of maximum electron density of F region at noon with solar activity is carefully investigated, during the years 1937-1957 for both long-term and month-to-month variations, in all existing observatories. On the basis of noon-equilibrium between electron loss and ion production by solar radiation, the presence of an ionizing effect, strongly dependent of the solar activity and peaked at latitudes of 55^{o} to 65^{o} is shown.

This latitudinal variation suggests a corpuscular origin of such ionizing effect. The possible source of a corpuscular flux is discussed. The energy of the ionizing particles is in the range of keVs. Quantitative evidence is given that Van Allen belts could be an important, or possibly the main, source.

AUTHOR

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1. Introduction

Recent studies (Mariani 1959 and 1960, here indicated as M1 and M2) on the variations of electron density distribution in the F2 layer suggest some latitudinal effect in its correlation with solar activity, in addition to that which can be correlated with the latitudinal and eleven-year variations of the ultraviolet radiation from the sun. The interpretation of these results is rather difficult because the experimental data can be more or less affected by other than solar causes (local variations of atmospheric temperature and winds, diffusion, etc.). Moreover, in the study of long series of ionospheric data, one cannot completely eliminate the "regular" effect due to the seasonal variation of zenithal distance of the sun. Considering the above difficulties, it is appropriate to apply statistical methods to the data of all existing observatories, which can give indications on a synoptic basis. In this way local irregularities and systematic effects in a number of observatories are thus easily recognizable and some general conclusions can be drawn.

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It is the purpose of this paper to apply a statistical analysis to all ionospheric data collected in the two eleven-year periods, 1937-1947 and 1947-1957.

2. Experimental data and method of analysis

In this study, we used the monthly median values of foF2 at noon for about seventy observatories, indicated in Table 1, whose data are published by the CRPL of the National Bureau of Standards or directly by the observatories.

Concerning the data of solar activity we used the monthly means of final sunspot numbers and of sunspot areas, published by the observatories of Zurich and Washington respectively; the monthly mean areas of hydrogen filaments and hydrogen and calcium flocculi, deduced from the character numbers published by the Astrophysical Observatory of Arcetri; the monthly values of heliographic distribution of chromospheric activity published by the observatory of Meudon. Details on the above parameters of solar activity are given elsewhere. The method of analysis is the same as in previous papers M1 and M2.

Following is a list of symbols:

N = monthly median values of $(foF2)^2$, in $(Mc/s)^2$

N_{12} = seasonal (twelve-month) variation of N

R = monthly mean of sunspot number

A_R = monthly mean of sunspot area

A_F = monthly mean of hydrogen-filament area

$A_{\Phi H}$ = monthly mean of hydrogen-flocculi area

$A_{\Phi Ca}$ = monthly mean of calcium-flocculi area

A_i = one of the above quantities R, A_R, A_F, etc.

When the above symbols have a bar (for example $\overline{N}$, $\overline{A}_F$, etc.) they represent the calculated corresponding value for the long-term (eleven-year) variation.

3. The correlation of F2 layer maximum electron density at noon with solar activity

We considered for each observatory simple and double linear regressions of the maximum electron density at noon with one solar parameter A_i (or two, different, A_i and A_j) expressed in the analytical form

$$\overline{N} = \overline{N}_o \ (1 + \overline{\alpha}_i \ \overline{A}_i) \tag{1}$$

$$\overline{N} = \overline{N}_o \ (1 + \overline{\beta}_i \ \overline{A}_i + \overline{\gamma}_j \ \overline{A}_j) \tag{2}$$

for long-term variations or,

$$N - N_{12} = (N - N_{12})_o (1 + \alpha_i \ A_i) \tag{3}$$

$$N - N_{12} = (N - N_{12})_o (1 + \beta_i \ A_i + \gamma_j \ A_j) \tag{4}$$

for actual month-to-month variations.

The quantities $\overline{N}_0$ and $(N - N_{12})_0$, represent the values deduced from the secular variation and from the month-to-month variation $N - N_{12}$ at minimum solar activity ($A_i = 0$), i.e. the electron density for an absolutely quiet Sun.

In M1 we found for the years 1947-1954 a remarkable dependence of $\overline{N}$ and $N - N_{12}$ upon the areas A_F of hydrogen filaments, after eliminating the dependence upon the sunspot number; a rough confirmation of this result was obtained in M2 from the few available data corresponding to the years 1938-1944. Comparison of results for northern and southern hemispheres indicated a noticeable asymmetry in the correlations with A_F, and in any case a clear latitudinal effect with a minimum at the equator.

In order to improve the above results and to search if they also apply to other phases of the solar cycle, in this paper we investigated the correlations of electron densities with as many as possible solar parameters. At first, we calculated the simple correlations of the electron densities with the sunspot number R, the areas A_R, A_F, $A_{\Phi H}$ and $A_{\Phi Ca}$; after we looked for the eventual effects of the position of the perturbation centers on the solar disk, investigating some oorrelations with the Meudon filament activity.

The results of such calculations as a whole give a conclusive confirmation of a latitudinal effect of the regression coefficients in the four year intervals 1938-1944, 1944-1947, 1947-1954, 1954-1957 which correspond alternatively to decreasing and increasing phases of solar cycle.

For a few observatories we could have only qualitative rather than quantitative information, essentially because of lack of sufficient data. These cases are not included in the quantitative results we give in the next sections.

We consider separately the cases of the long-term and month-to-month variations.

3.1 <u>The case of long-term variation $\overline{N}$</u>

The principal results are given in Figures 1, 2 and 3 in which we show the quantities $\overline{N}_o$ and $\overline{\alpha}_i$ defined by (1) for the simple correlations of $\overline{N}$ with the sunspot number $\overline{R}$ (Figure 1), the area $\overline{A}_F$ (Figure 2) and the areas $\overline{A}_{\Phi H}$ and $\overline{A}_{\Phi Ca}$ (Figure 3), respectively. In all the diagrams we indicated on the abscissae an "effective" latitude defined as arithmetical mean of geographical and geomagnetic latitudes. As we already found in M1, such a choice leads to some reduction of minor irregularities in the distribution of the points on the graphs and takes into some account the dependence of the electron density upon both the geographical and geomagnetic coordinates.

In the left hand of each figure we show the values of $\overline{N}_o$; in the right one the values of $\overline{\alpha}_i$. For all the calculated points the amplitude of the standard errors is given.

A first interesting feature is the rather symmetrical distribution of $\overline{N}_o$ in the two hemispheres for latitudes greater than 20^o. In the tropical latitude belt the quantity $\overline{N}_o$ exhibits two relative maxima; the maximum in the northern hemisphere is rather localized; the position of the southern hemisphere maximum does not clearly appear because of the lack of sufficient experimental data at those latitudes. The occurrence of such maxima in the tropical region is a long known feature of F2 layer.

We can also compare the latitudinal variation of $\overline{N}_o$ and the annual mean of cos χ_{noon}, where χ_{noon} is the noon zenithal distance of the sun. The values of cos χ_{noon}, which is proportional to the noon ionization intensity and, for the F2 layer, approximately also to the noon electron density, have been calculated (Figure 4) taking into consideration the sphericity of the earth and sunlight at ionospheric levels, even during polar winter, at noon, in all the northern observatories. By use of proper normalization factors, we obtain a rather good fit of the experimental values $\overline{N}_0$ with the annual mean of $\cos \chi_{noon}$ for latitudes higher than $30^o - 35^o$.

Some anomalous values are present in the latitudinal distribution of $\overline{N}_0$, in particular the rather high values at Huancayo and Leopoldville, which are at or very close to the geomagnetic equator. Generally, as we said, local conditions such as upper atmospheric winds, anomalous temperature or concentration distribution, influence more or less the electron density so that, at this stage, we try to give a physical meaning to the general behavior rather than to some particular anomaly, which has instead to be considered in a more refined theory. In the particular case of equatorial data, we remember that the geomagnetic field also exhibits an anomalous behavior on the geomagnetic equator, due to the equatorial electrojet at ionospheric levels.

We conclude that the values $\overline{N}_0$, for latitudes higher than $30^o - 35^o$ are a rather good index of the steady ultra-violet radiation at F2 layer levels.

If we take now into account the latitudinal variation of the regression coefficients $\overline{\alpha}_i$, assuming a dependence of $\overline{N}$ on the solar activity as given in (1), we would expect, within the statistical and experimental errors, constant values at all latitudes. This is not the case, because a remarkable latitudinal effect is apparent.

A first interesting feature appearing in this latitudinal variation of the coefficients $\overline{\alpha}_i$ is an appreciable difference of their values in the northern and southern hemispheres, when we consider the correlation of $\overline{N}$ with $\overline{R}$ or $\overline{A}_F$. However, this is not the case for correlations with $\overline{A}_{\Phi H}$ or $\overline{A}_{\Phi Ca}$. The existence of some difference between northern and southern hemispheres was already shown in M1 during the years 1947-1954. However, it may be only apparent, due to the particular choice of the solar parameters. Actually, the areas $\overline{A}_{\Phi H}$ and $\overline{A}_{\Phi Ca}$ may be a better index of solar activity than $\overline{R}$ and $\overline{A}_F$, used in M1.

The most surprising feature of the latitudinal effect is the sharp maximum of $\overline{\alpha}_i$ at latitudes of 55^o - 60^o. At first sight, an increase of $\overline{\alpha}_i$ for increasing latitudes could be due to the decreasing values of $\overline{N}_o$. Although such an effect can to some extent affect the variation of $\overline{\alpha}_i$, it does not seem to be the determining factor. The reason for this conclusion is that at northern latitudes higher than 60^o, $\overline{\alpha}_i$ first decreases remarkably and very steeply and then recovers to the equatorial values. For higher southern latitudes the decrease of $\overline{\alpha}_i$ cannot be checked because of the lack of data; only its increase til 55^o is observed.

A simple physical explanation of the above latitudinal effect could be given in terms of two superimposed effects. The first is a solar cycle variation of ultraviolet radiation, which is present in all the places, the other is a latitudinal variation probably due to a corpuscular radiation directly or indirectly coming from or influenced by the sun. If this is the case, one can study the latitudinal variation of the absolute "corpuscular" effect.

We can write equation (1) in the form

$$\overline{N} = \overline{N}_o \left[1 + a_i \overline{A}_i\right] + \overline{N}_o(\overline{\alpha}_i - a_i) \overline{A}_i \tag{5}$$

where the first term represents the "ultraviolet" effect and the last one the "corpuscular" effect; the quantity a_i is assumed to be independent of the latitude. A possible value of a_i may be the mean of calculated $\overline{\alpha}_i$ for the tropical belt of latitudes, which is practically the same as that for very high latitudes.

A clear latitudinal effect is again apparent not only in $\overline{\alpha}_i - a_i$, but, above all, in $\overline{N}_o(\overline{\alpha}_i - a_i)$. This last feature gives further evidence of a latitude effect on the absolute intensity of the "corpuscular" effect. For reasons of brevity we do not give diagrams of $\overline{N}_o(\overline{\alpha}_i - a_i)$; in the following, we will rather consider the correlations of month-to-month variation which we study in the next section and, from the physical point of view, are much more significant.

It should be emphasized that the $\bar{\alpha}_i$ distribution has its maximum at lower latitudes than the auroral zone; the lines of force between the geomagnetic latitudes 30° and 65° cross the equatorial plane at geocentric distances of about 1.4 and 5.5 earth's radii, i.e. of 2500 and 29,000 km on the ground. At least from a qualitative point of view, one could think in terms of some connection between corpuscular ionospheric effects and Van Allen radiation belts. We shall consider this point in the section 4.

The double correlation with $\bar{R}$ and $\bar{A}_F$, defined by (2) was also tested, for the years 1944-1947 and 1954-1957; the same double correlation with $\bar{R}$ and $\bar{A}_F$, for the years 1947-1954 was already considered in M1. For the latter time interval a latitudinal constancy of $\bar{\beta}_R$ and a latitudinal variation of $\bar{\gamma}_F$ was established: such a feature is not confirmed during the two increasing phases of the solar cycle, so that it has to be considered as a non-permanent feature.

3.2 The case of the month-to-month variation $N - N_{12}$

This case is more expressive from the physical point of view, because it takes into account the actual not-smoothed month-to-month variation of both electron density and solar parameters.

The results of our calculations are shown in Figures 5, 6 and 7. In this case, obviously, the statistical errors are about an order of magnitude greater than in the case of long-term variation. The essential features of the behaviors of $(N - N_{12})_o$ and α_i are well apparent. A statistical improvement for a sufficient amount of ionospheric data can be obtained considering the eleven-year period 1947-1957. The mean values of α_i for correlations with monthly values of R and A_F are again greater in the northern than in the southern hemisphere, while this is not the case for the correlations with $A_{\Phi H}$ and $A_{\Phi Ca}$ (Figure 7).

If we again assume a mean value a_i of α_i for the tropical belt of latitudes, we can write the regression equation (3) in the form

$$N - N_{12} = (N - N_{12})_o \, [1 + a_i \, A_i + (\alpha_i - a_i) \, A_i]. \qquad (6)$$

Figure 8 shows the 1947-1957 behavior of $(N - N_{12})_o(\alpha_i - a_i)$ which represents, as we have already seen, an index of the absolute latitudinal effect on the ionospheric electron density.

Although the statistical errors are much greater because of the combination of the errors on $(N - N_{12})_o$ with those on α_i and a_i, the latitudinal effect is clearly enhanced.

For the double correlation defined by (4), however, we again failed to obtain results having some clear physical meaning.

3.3 In order to look for an eventual dependence of ionospheric electron density upon the heliographic latitude of the perturbation centers on the solar disk, we had the opportunity of studying the data on filaments activity collected by the observatory of Meudon, as a function of heliographic coordinates. Such data are given for each solar rotation period, so that we had to express them in terms of terrestrial months, making a weighted mean as follows: if in a terrestrial month there are contained n days of the 27 days of a solar rotation period and m days of the following rotation period, and x and y are the numbers which express the filament activity for the two rotations, the mean terrestrial-month activity is $\frac{n x + m y}{n + m}$.

We have separately considered the activity of: (i) polar filaments; (ii) equatorial filaments; (iii) filaments between the heliographic latitudes 30^{o} N to 30^{o} S; (iv) filaments in the northern solar hemisphere; (v) filaments in the southern solar hemisphere.

In each case, the correlations we attempted do not seem physically significant because the values of the coefficients of the linear regressions (1) and (3) exhibit noticeable and at all irregular differences for different observatories; in many cases also negative values of $\overline{N}_o$ and $(N - N_{12})_o$ were obtained.

Based on the present investigation, no significant correlation between ionospheric F2 layer and latitudinal distribution of solar activity centers appears to exist.

4. The interpretation of the latitudinal effect

4.1 On the basis of the conclusion drawn from the results of section 3, we give a tentative physical interpretation of the latitudinal effect according to the following hypotheses:

(i) the effect is caused by a corpuscular radiation impinging, with a characteristic latitudinal distribution, upon the upper atmosphere;

(ii) the corpuscular radiation has a rather low mean energy (of the order of keVs or tens of keV), so that it reaches the 200 km level, i.e. the F2 layer, but does not necessarily reach the E layer (Mariani, 1957);

(iii) the intensity of the radiation depends (as first approximation) linearly on the solar activity.

First, we estimate the order of magnitude of the particle flux necessary to give the actual ionization rate. We assume that a particle loses all its energy in ionization of neutral particles.

In the steady state which we may assume for the F2 layer at noon, we write the equilibrium equation in the form

$$I - bn_e = 0 \qquad (7)$$

where I is the production rate, b is the effective recombination coefficient and n_e the electron density. Noting that the maximum values of the ratios $(\alpha_i - a_i)/a_i$, at latitudes of 55-60^o, have generally values between 1 and 2, one concludes that the effects of the variable part of the ultraviolet radiation and that of the corpuscular radiation are comparable. However, the total ultraviolet contribution, proportional to $1 + \alpha_i A_i$, becomes more and more important with respect to the corpuscular contribution as the solar activity decreases. At maximum solar activity (conventional value of sunspot number R = 150) the quantities $1 + \alpha_i A_i$ and $\alpha_i - a_i$ are about the same; in this physical situation, the corpuscular ionization rate I_c is comparable to the ionization rate I_u of the ultraviolet radiation.

Thus we have

$$I_u \cong I_c \cong \frac{I}{2} \cong b\,\frac{n_e}{2} \tag{8}$$

so that if we put $b = 10^{-4}$ sec^{-1} and $n_e = 10^6$ cm^{-3}, i.e. the ionospheric layer has a critical frequency $f_c \cong 9$ Mc/sec, we obtain, at the height of maximum electron density (i.e. at 300-350 km):

$$I_u \cong I_c \cong 50 \text{ ions cm}^{-3} \text{ sec}^{-1}$$

We now make use of the fact that the photoionization rate at heights more than 300 km decreases exponentially (Watanabe and Hinteregger, 1962). We assume that above this altitude 50% of the ionization is due to corpuscular radiation. Thus an estimate of the total corpuscular ionization in a square cm column of air above 300 km, at middle latitudes can be $I_{total} \cong 2 \times 10^9$ ions cm^{-2} sec^{-1}. If the mean ionization loss is 35 eV/ion-pair, the corresponding kinetic energy flux is $F_T \cong 7 \times 10^{10}$eV cm^{-2} sec^{-1} $\cong$ 0.1 erg cm^{-2} sec^{-1}. For comparison the total energetic flux entering the atmosphere, assuming the solar constant = 2 cal cm^{-2} min^{-1} is 1.4×10^6 erg cm^{-2} sec^{-1}.

The above data allow a simple evaluation of the order of magnitude of the required particle flux. If the particles can penetrate vertically to a minimum altitude of 150 km, they have, if they are electrons, a kinetic energy $T \cong 1500$ eV. However, the effect of scattering and of the geomagnetic field is that the path of the electrons is not a vertical straight line so that, on the average, they stop at rather higher altitudes, i.e. in the F layer. The total incoming electron flux F_e, at maximum solar activity, can be estimated as

$$F_e = \frac{F_T}{1500} \cong 5 \times 10^7 \text{ electrons cm}^{-2} \text{ sec}^{-1}$$

The velocity of an electron having an energy $T \cong 1500$ eV is $v \cong 2.3 \times 10^9$ cm sec^{-1} so that the particle density in the incoming stream is of the order of 10^{-2} cm^{-3}.

If such a corpuscular radiation impinge uniformly the upper atmosphere, between the latitudes of 30° and 65°, i.e. a surface of 1/3 of the total area of the earth, the total incoming flux is of the order of 10^{26} electrons sec^{-1}.

In view of its intensity, it does not seem possible to attribute such a flux of electrons to a primary source other than the sun. On the other hand, the particular features of the latitudinal effect exclude that they are incoming directly from the sun along Störmer-trajectories. As we said, we may assume that the electrons are leaking from the Van Allen radiation belts.

We had the opportunity to use the low energy electron fluxes measured by Krasovskii et.al. (1962) and, more recently, by O'Brien (1962). During one pass of Sputnik 3 Krasovskii reported, at 45^{o} of geomagnetic latitude an energy flux of dumped electrons of energy $T \cong 10$ keV between 10^{-2} and 1 erg cm^{-2} sec^{-1}. The more systematic measurements of O'Brien made on Injun I, gave median fluxes of 10^{6} trapped electrons cm^{-2} sec^{-1} with $T \geq 40$ keV; corresponding to these intensities, O'Brien reports average energy fluxes at trapped electrons with $T \geq 1$ keV of the order of 1 to 10 erg cm^{-2} sec^{-1}. We notice that the above assumed electron energy of 1.5 keV is just the average energy if we assume, for energy ≥ 1 keV, a power law differential spectrum with an exponent $\gamma = 4$. Thus, the number fluxes of trapped electrons with mean energy $T = 1.5$ keV are of the order of 5×10^{9} cm^{-2} sec^{-1}; with "lifetimes" of 10^{3} to 10^{4} sec, as calculated by O'Brien for particles with $T > 40$ keV one gets dumped electron fluxes not less than 10^{5} to 10^{6} cm^{-2} sec^{-1}; the corresponding energy fluxes are not less than 10^{-4} to 10^{-3} erg cm^{-2} sec^{-1}.

If one considers that the measurements of O'Brien have been made in a period of reduced solar activity ($R = 50$) and that the "lifetime" of very low energy electrons may be substantially lower than that estimated for electrons with $T > 40$ keV, we can effectively consider the dumped electron flux from Van Allen belts as an important source (or the source) of the corpuscular radiation in the F2 layer. Some difficulty could arise from the fact that the corpuscular ionospheric effect decreases very sharply at latitudes higher than 60^{o}, while in practice the electron fluxes measured by O'Brien are nearly constant at all latitudes up to 70^{o}, corresponding to a maximum geocentric distance of about 10 earth radii.

Concerning this point, we must have in mind that our results give the situation of the ionosphere averaged on a solar cycle. One cannot exclude some small year to year shift of the latitude of maximum corpuscular effect, in particular towards lower latitudes as solar activity decreases. If this is the case, one can reasonably assume that at maximum solar activity the maximum corpuscular effect may occur at higher geomagnetic latitudes, 60 to 65^{o} or even higher.

A further quantitative element we can easily calculate is the integrated flux of particles during the entire eleven-year solar cycle. If we assume a linear long-term time variation, and remember that the above calculated flux values refer to the maximum solar activity, we estimate that the integrated electron flux entering the upper atmosphere may be 10^{34} electrons.

The corresponding integrated energy, assuming a mean energy of keVs, is 10^{25} to 10^{26} ergs.

One immediately sees that the above integrated fluxes of particles and energy represent only a very small part of the fluxes ultimately emitted from the sun during its full cycle of activity.

4.2 Finally, we want to draw attention to many experimental indications of rather intensive particle fluxes in the upper atmosphere. It is agreed that polar aurorae are the result of corpuscular radiation, although its origin is not fully understood.

Antonova and Ivanov-Kholodny (1961) point out the possibility of a corpuscular origin of nighttime ionospheric ionization: their calculated flux of electrons of $\sim$ 100 eV would be 10^{10} to 10^{11} electrons cm^{-2} sec^{-1} to which correspond an energy flux of 1 to 10 erg cm^{-2} sec^{-1}; these electron and energy fluxes are 10^3 to 10^4 higher than our minimum estimates. Such high fluxes, based on the assumption of a high value of the loss coefficient in the F2 layer (10^{-7} to 10^{-6} cm^3 sec^{-1}) are probably overestimated, since the actual coefficient appears to be much smaller.

Several experimental results (Bourdeau and Bauer, 1962) indicate that, at altitudes approximately between 150 and 350 km, the electron temperature is higher than the ion temperature.

Bourdeau (1962) points out that "large fluxes of quasi energetic particles which could provide an additional ionization source have been observed at some geographical locations in the upper atmosphere".

Harris and Priester (1962), in their calculated theoretical models for the solar-cycle variation of the upper atmosphere, assume an ultraviolet heat source and a corpuscular heat source, of almost equal magnitude, of the order of some erg cm^{-2} sec^{-1}; contrary to our scheme, however, the assumed ratio between corpuscular and ultraviolet fluxes does not vary during a solar cycle.

We conclude that if the electron flux we calculated in 4.1 is really present in the F2 layer, it could possibly originate in the radiation belts; in any case the Van Allen belts are a good reservoir of ionospheric ionizing particles. This possibility obviously does not exclude some other acceleration mechanism acting on very low energy electrons "normally" present in the upper atmosphere: for example, one could think in terms of an electric field, only or mainly in the latitude range in which the corpuscular effect is present. From a general point of view, it will be very interesting to study the eventual dependence of the corpuscular effect upon the local time, as has been done for the polar aurora. Actually, the experimental parameter, the

F2 layer critical frequency, is a more or less approximate index of ultraviolet and corpuscular radiation only near noon; at other times, particularly during the night, it is controlled primarily by other phenomena as time and height variations of recombination or attachment coefficients, temperature variations, convective motions, etc. so that it cannot be considered an even approximative index of the incoming corpuscular radiation. At present, the first and more immediate experimental problem would be the direct detection of very low energy particle flux at ionospheric levels; we hope that this can be made in the near future.

TABLE 1

Observatory	Geomag. Lat.	Coordinates Long.	Geograph. Lat.	Coordinates Long.
Clyde	82N	1E	70N	291E
Resolute Bay	82"	289"	75"	265"
Godhavn	80"	32"	69"	306"
Baker Lake	74"	315"	64"	264"
Narsassuaq	71"	38"	61"	315"
Reykjavik	70"	71"	64"	338"
Churchill	69"	323"	59"	266"
Point Barrow	68"	241"	71"	203"
Tromso	67"	117"	70"	19"
Kiruna	65"	116"	68"	20"
College (Fairbanks)	65"	256"	65"	148"
Anchorage	61"	258"	61"	210"
Inverness	61"	83"	57"	356"
Oslo	60"	11"	60"	100"
Winnipeg	60"	323"	50"	263"
Uppsala	59"	106"	60"	18"
St. John	59"	21"	48"	307"
Prince Rupert	58"	283"	54"	230"
Ottawa	57"	351"	45"	284"
Leningrad	56"	118"	60"	31"

Observatory	Geomag. Lat.	Coordinates Long.	Geograph. Lat.	Coordinates Long.
Slough	54N	83E	51N	359E
De Bilt	54"	89"	52"	5"
Lindau	52"	94"	52"	10"
Moscow	50"	121"	55"	37"
Freiburg	50"	90"	48"	8"
Washington	50"	350"	39"	283"
Poitiers	49"	82"	47"	0"
Schwarzenburg	48"	89"	47"	7"
Adak	47"	240"	52"	183"
Graz	47"	97"	47"	15"
Tomsk	45"	160"	56"	85"
San Francisco	44"	298"	37"	238"
White Sands	41"	316"	33"	253"
Baton Rouge	41"	334"	30"	269"
Casablanca	38"	69"	34"	352"
Wakkanai	35"	206"	45"	142"
Alma Ata	33"	152"	43"	77"
Portorico	30"	2"	18"	293"
Akita	29"	205"	40"	140"
Tokyo	25"	206"	36"	140"
Yamagawa	21"	198"	31"	131"
Dakar	21"	55"	14"	343"

Observatory	Geomag. Lat.	Coordinates Long.	Geograph. Lat.	Coordinates Long.
Maui	21N	268E	21N	203E
Panama	21"	348"	9"	280"
Delhi	19"	149"	29"	77"
Okinawa	15"	196"	26"	128"
Formosa	14"	189"	25"	121"
Ibadan	11"	75"	7"	4"
Bombay	10"	144"	19"	73"
Djibouti	7"	114"	11"	43"
Baguio	5"	189"	16"	121"
Madras	3"	150"	13"	80"
Guam	3"	212"	13"	145"
Tiruchy	1"	148"	11"	79"
Huancayo	0.6S	354"	12S	285"
Leopoldville	3"	84"	4"	15"
Singapore	10"	173"	1N	104"
Rarotonga	21"	274"	21S	200"
Buenos Ayres	23"	9"	35"	302"
Tananarive	24"	113"	19"	48"
Johannesburg	27"	91"	26"	28"
Capetown	33"	80"	34"	18"
Brisbane	36"	227"	27"	153"
Falkland Is.	40"	9"	52"	302"

Observatory	Geomag. Lat.	Coordinates Long.	Geograph. Lat.	Coordinates Long.
Watheroo	42S	186E	30S	116E
Canberra	44"	225"	35"	149"
Christchurch	48"	253"	44"	173"
Hobart	52"	225"	43"	147"
Decepcion	52"	7"	63"	299"
Port Lockroy	53"	4"	65"	297"
Campbell Is.	57"	253"	53"	169"
Macquarie Is.	61"	243"	54"	159"
Terre Adelie	75"	231"	67"	140"

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CAPTIONS FOR THE FIGURES

Figure 1 - Correlation of the long-term variation $\overline{N}$ and $\overline{R}$. On the abscissae, in this figure and in the following figures 2, 3, 5, 6, 7 and 8, the "effective" latitude.

Figure 2 - Correlation of the long-term variation $\overline{N}$ and $\overline{A}_F$.

Figure 3 - Correlation of the long-term variation $\overline{N}$ and $\overline{A}_{\Phi H}$. (upper graphs) and $\overline{N}$ and $\overline{A}_{\Phi Ca}$ (lower graphs).

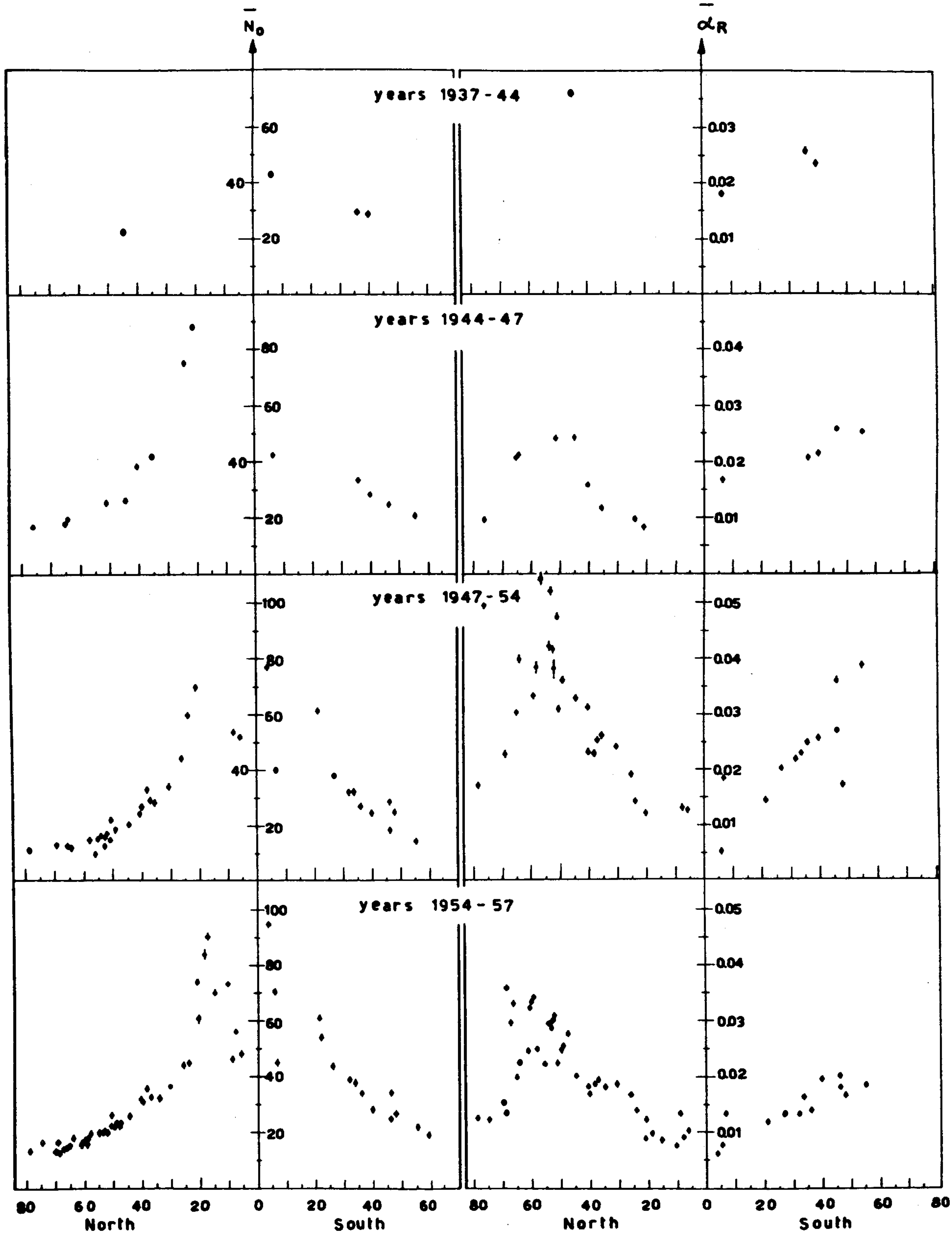
Figure 4 - Latitudinal variation of annual mean of cos χ_{noon} (curve A) and of the amplitude of its seasonal variation (curve B); on the abscissae the geographical latitude.

Figure 5 - Correlation of month-to-month variation $N-N_{12}$ and R.

Figure 6 - Correlations of month-to-month variation $N-N_{12}$ and A_F.

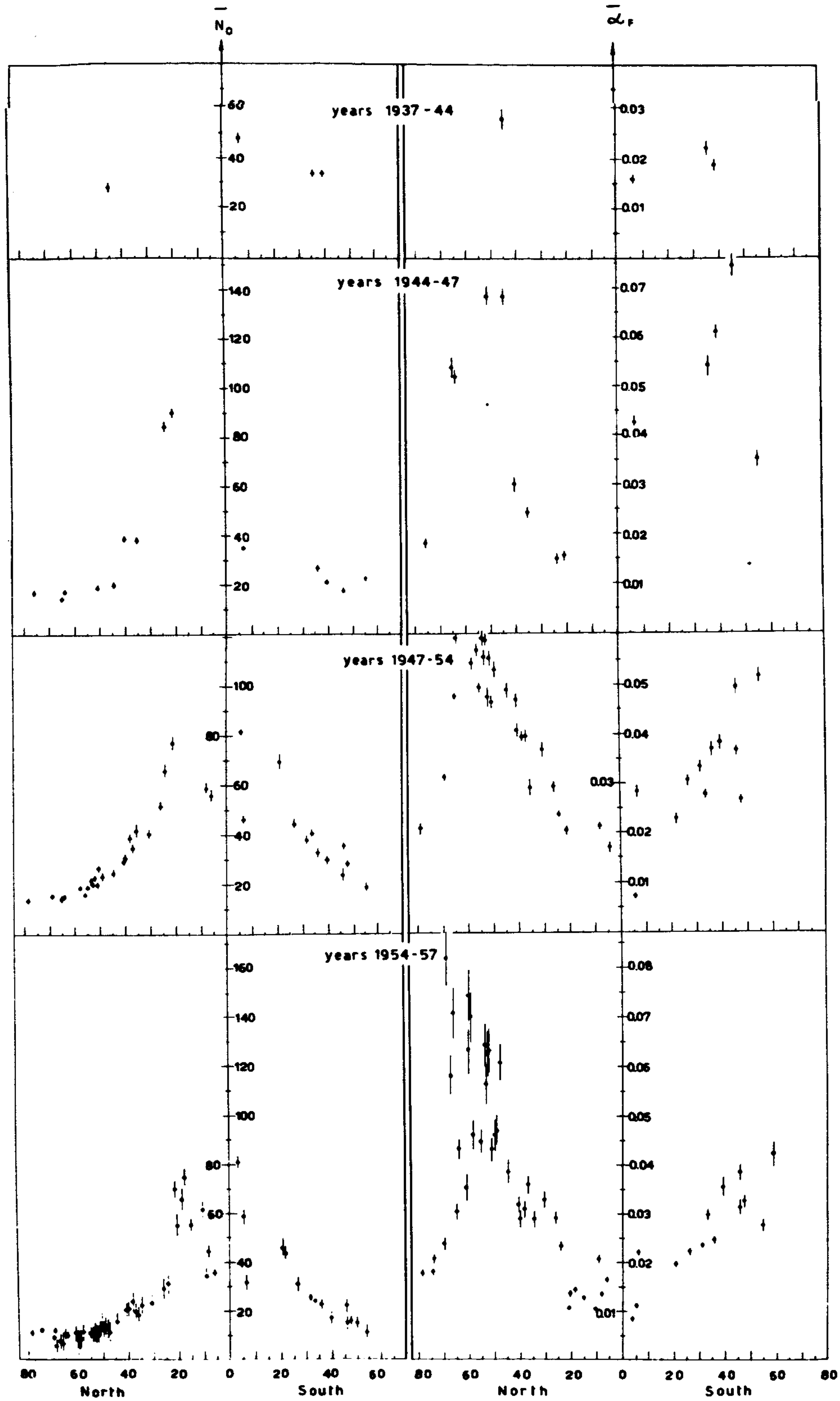
Figure 7 - Correlation of month-to-month variation $N-N_{12}$ and $A_{\Phi H}$.(upper graphs) and $N-N_{12}$ and $A_{\Phi Ca}$ (lower graphs).

Figure 8 - Latitudinal variation of $(N-N_{12})_o\,(\alpha_i - a_i)$ for the eleven years 1947-1957. The values at latitude 59^o S refer to the years 1954-1957.



$\bar{N}_0$
$\bar{\alpha}_R$
years 1937 - 44
years 1944 - 47
years 1947 - 54
years 1954 - 57
North
South
North
South

Figure 1



$\overline{N}_0$
$\overline{\alpha}_F$
years 1937-44
years 1944-47
years 1947-54
years 1954-57
North
South
North
South

Figure 2

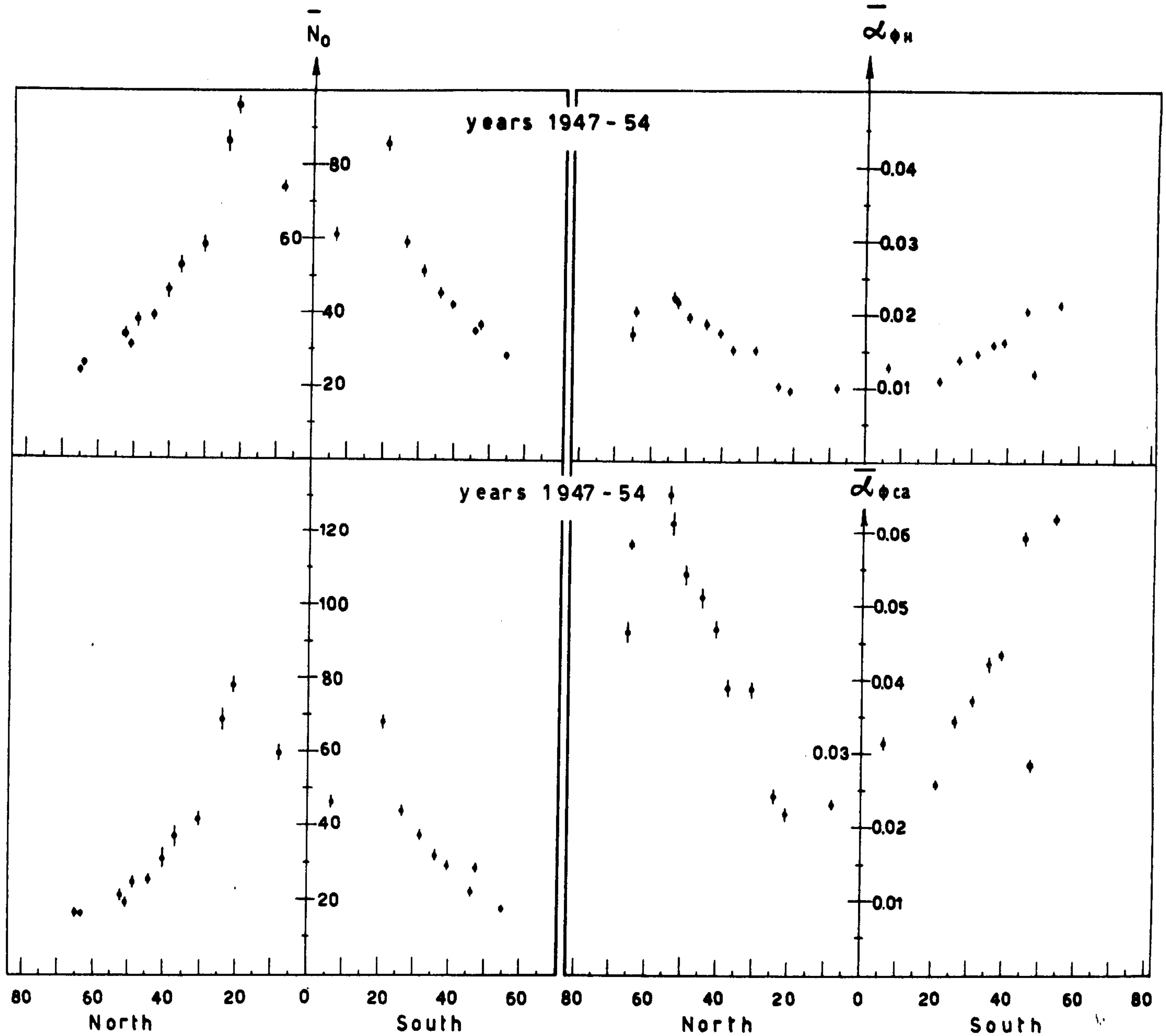

$\bar{N}_0$
$\bar{\alpha}_{\phi H}$
years 1947 - 54
years 1947 - 54
$\bar{\alpha}_{\phi ca}$
North
South
North
South

Figure 3

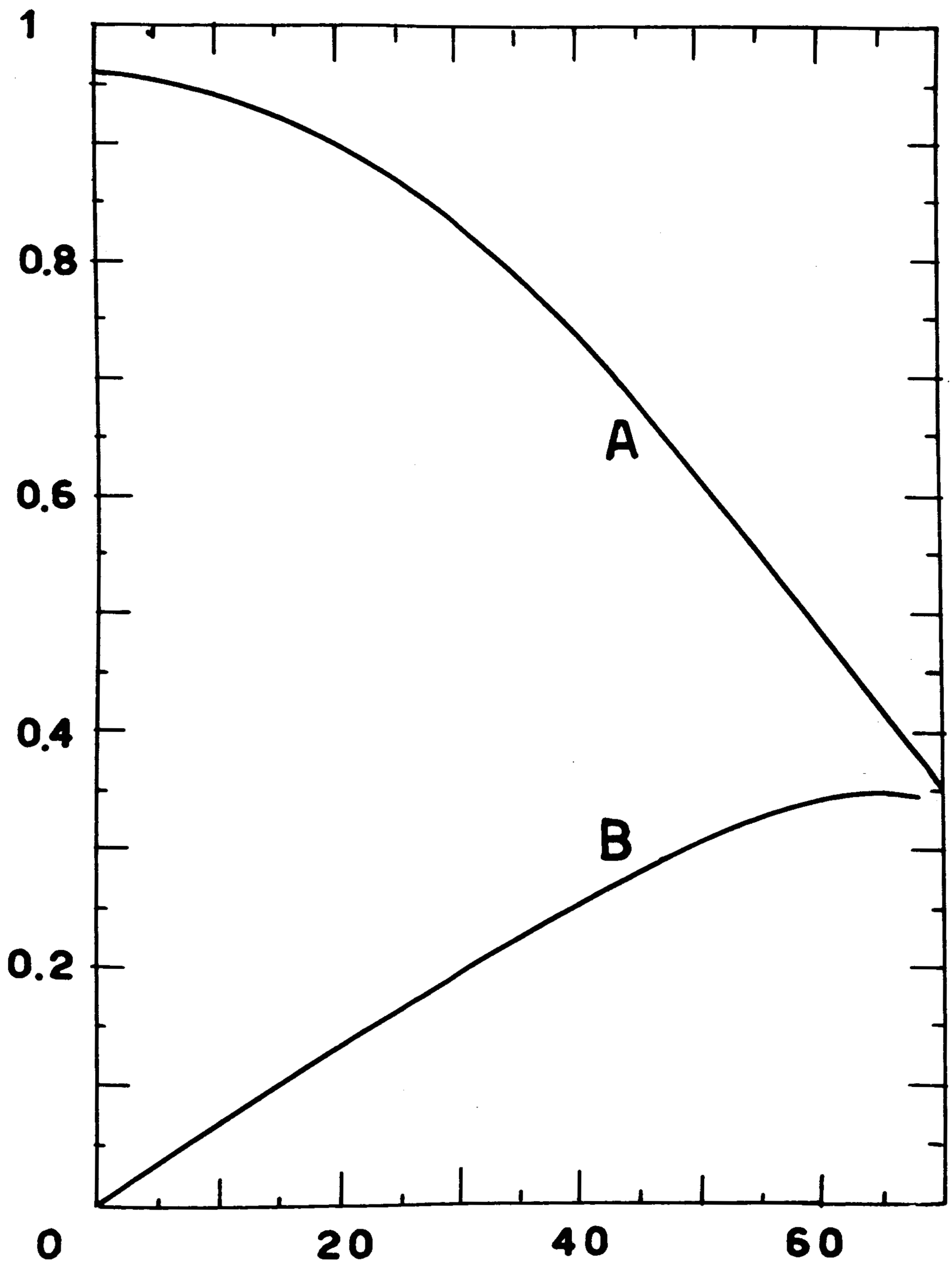
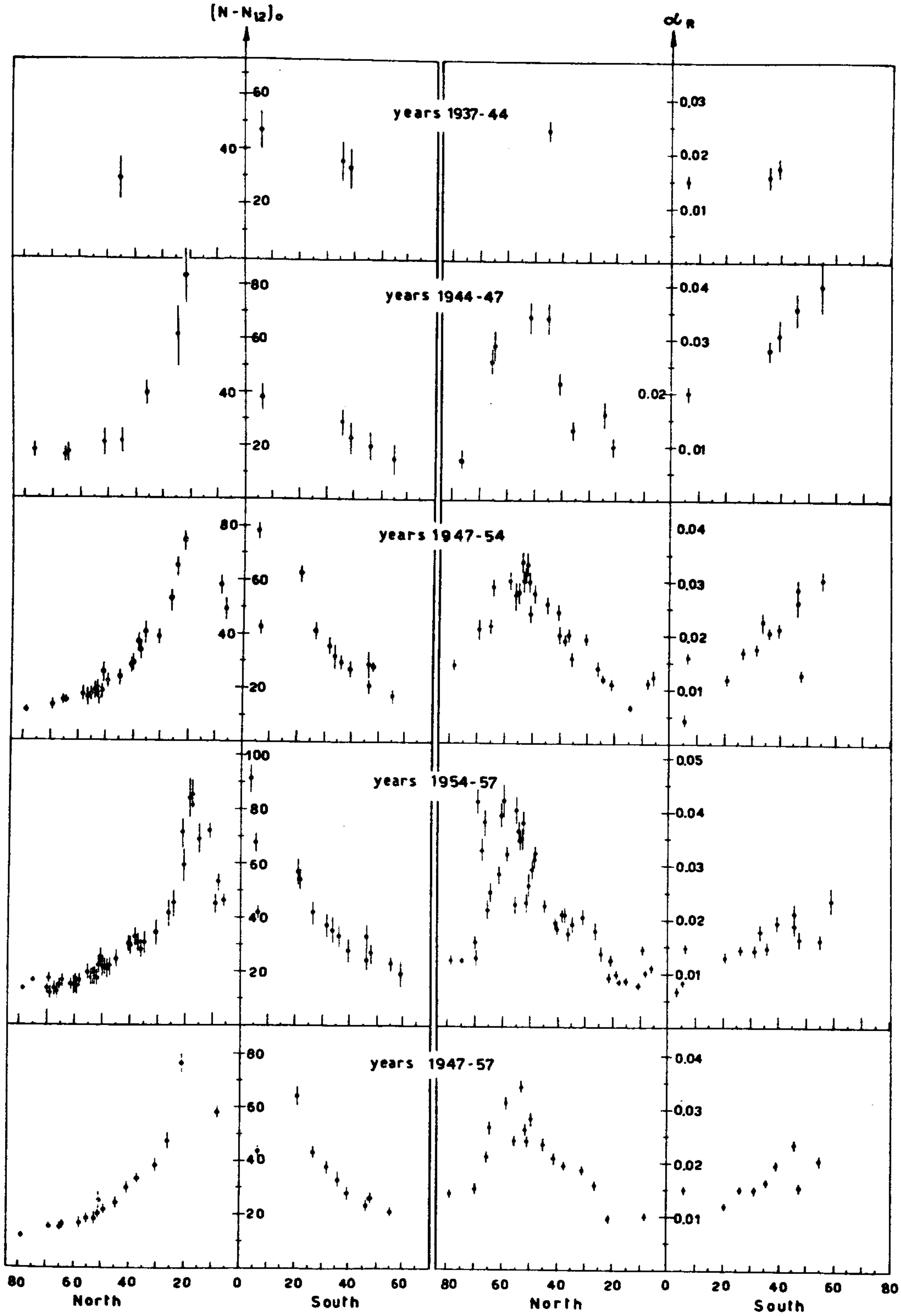
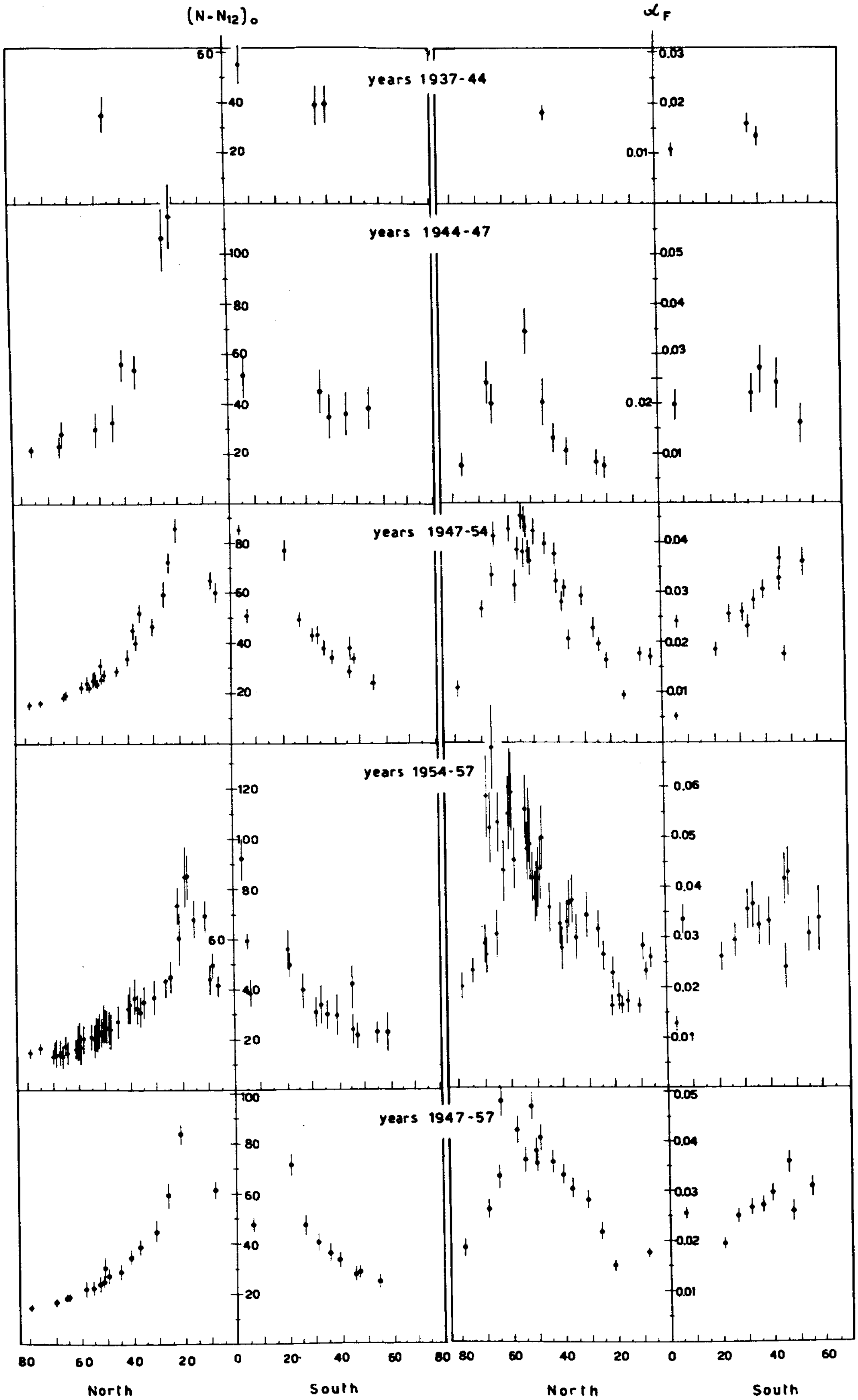


Figure 4



(N - N12)0
αR
years 1937-44
years 1944-47
years 1947-54
years 1954-57
years 1947-57
North
South
North
South

Figure 5



(N-N12)o
αF
years 1937-44
years 1944-47
years 1947-54
years 1954-57
years 1947-57
North
South
North
South

Figure 6

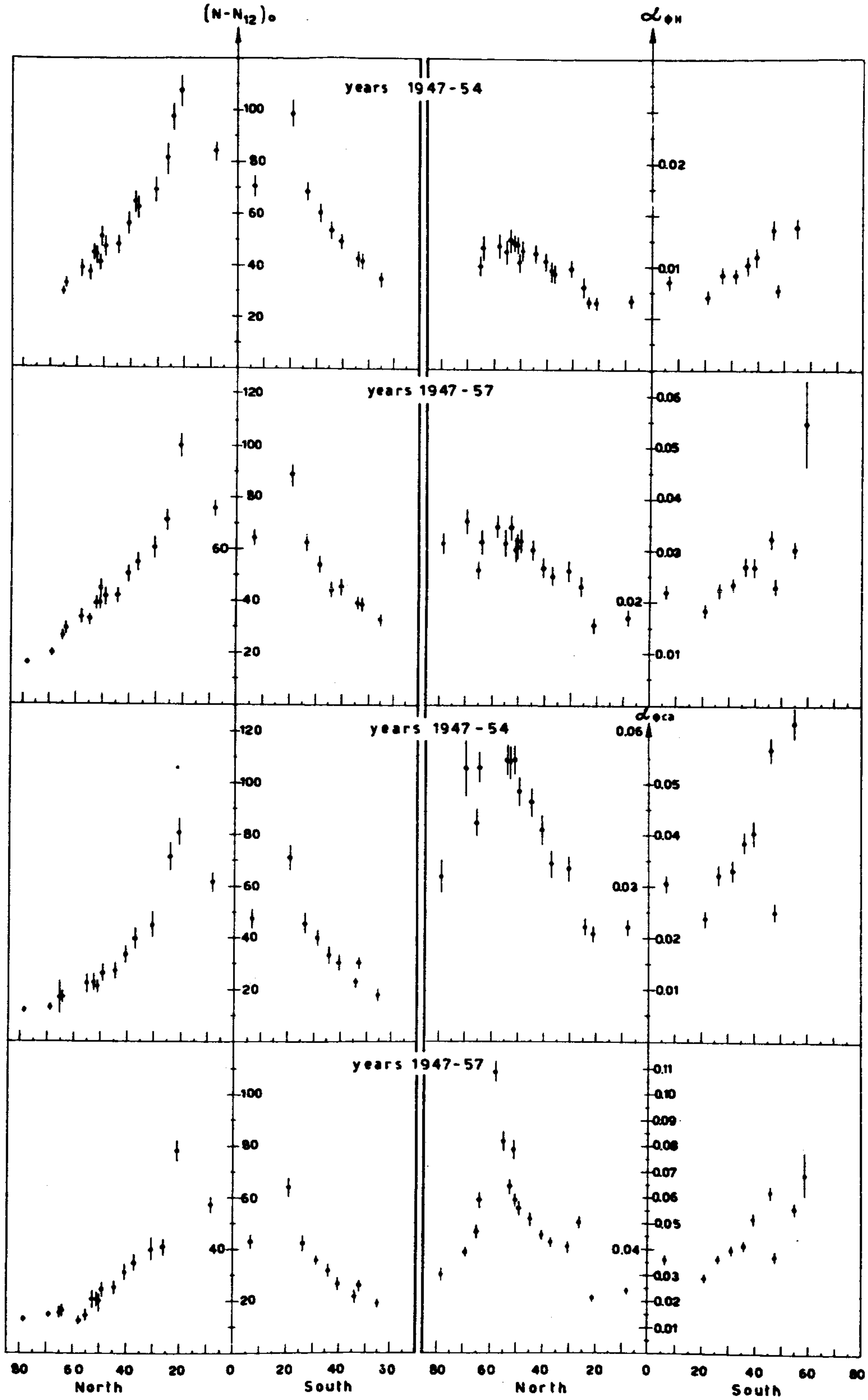
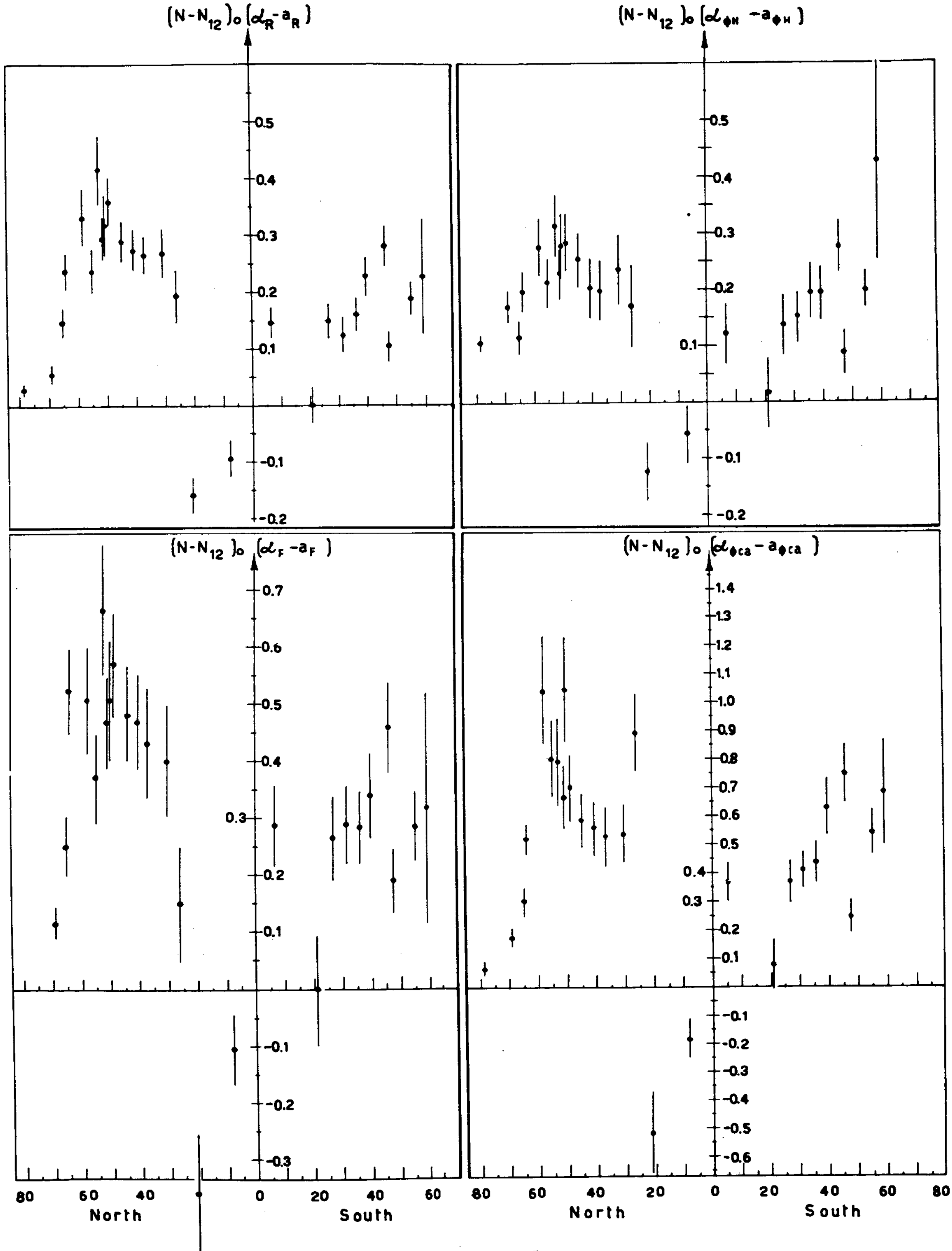

(N-N12)o
α φH
years 1947-54
years 1947-57
years 1947-54
α φCa
years 1947-57
80 60 40 20 0 20 40 30
North
South
80 60 40 20 0 20 40 60 80
North
South

Figure 7



$(N-N_{12})_o\,(\alpha_R - a_R)$
$(N-N_{12})_o\,(\alpha_{\phi H} - a_{\phi H})$
$(N-N_{12})_o\,(\alpha_F - a_F)$
$(N-N_{12})_o\,(\alpha_{\phi ca} - a_{\phi ca})$
80
60
40
North
0
20
40
60
South
80

Figure 8